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Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments

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How will the global atmosphere and climate be protected? Achieving net-zero CO_2 emissions will require carbon capture and storage (CCS) to reduce current GHG emission rates, and negative emissions technology (NET) to recapture previously emitted greenhouse gases. Delivering NET requires radical cost and regulatory innovation to impact on climate mitigation. Present NET exemplars are few, are at small-scale and not deployable within a decade, with the exception of rock weathering, or direct injection of CO_2 into selected ocean water masses. To keep warming less than 2°C, bioenergy with CCS (BECCS) has been modelled but does not yet exist at industrial scale. CCS already exists in many forms and at low cost. However, CCS has no political drivers to enforce its deployment. We make a new analysis of all global CCS projects and model the build rate out to 2050, deducing this is 100 times too slow. Our projection to 2050 captures just 700 Mt $CO_2\,yr^{-1}$, not the minimum 6000 Mt $CO_2\,yr^{-1}$ required to meet the 2°C target. Hence new policies are needed to incentivize commercial CCS. A first urgent action for all countries is to commercially assess their CO_2 storage. A second simple action is to assign a Certificate of CO_2 Storage onto producers of fossil carbon, mandating a progressively increasing proportion of CO_2 to be stored. No CCS means no 2°C.

This article is part of the theme issue 'The Paris Agreement: understanding the physical and social challenges for a warming world of 1.5°C above pre-industrial levels'.

1. The need, challenge and timescale

Commercial reserves of fossil carbon are immense, equivalent to approximately 3 trillion tonnes of CO_2. Carbon resources are 30–50 times larger than reserves [1] including difficult to extract conventional hydrocarbons, plus unconventional hydrocarbon, methane hydrates in permafrost and hydrates frozen beneath continental margin sea beds. Any one of these reservoirs of fossil carbon is more than enough to take the cumulative total of anthropogenic carbon emissions because of industrialization beyond the '1 trillion tonne carbon' limit approximating to 2°C of average global warming [2]. Staying within that limit means that global emissions need to reduce at about 3% yr^{-1} from now (37 Gt CO_2 yr^{-1}) to a net balance of zero around 2050. Illustrating this as a simplistic linear trend means reducing emissions, or extracting CO_2 from the atmosphere, by an additional 1100 Mt CO_2 yr^{-1} year on year. Thus, 1.1 Gt CO_2 yr^{-1} in year 1, 2.2 Gt CO_2 yr^{-1} in year 2, 3.3 Gt CO_2 yr^{-1} in year 3. This is a vast increase in removal or reduction of CO_2 required each year, equivalent to about half of the global emissions drop due to the 2008 recession. This analysis also neglects that annual emission rates before 2035 may increase by 35% due to increasing global wealth and energy use. An alternative analogy is that, by mid-century, each citizen of an industrialized nation would need to maintain their lifestyle with the carbon emissions of a citizen of India today. In an International Energy Agency (IEA) 2°C pathway for energy, carbon capture and storage (CCS) is tasked with capturing 6000 Mt CO_2 yr^{-1} by 2050. CCS is feasible, and technically demonstrated, but only 15 purposed CCS projects exist to date, due to the absence of markets, lack of political drive and lack of investment confidence to build the precursor infrastructure required [2].

An alternative way to consider how to remain within a 2°C warming limit is to look at the cumulative total amount of carbon that can be emitted. Simulations suggest that fewer than 200–400 GtC can now be released into the atmosphere [3]. That is in perpetuity. Most effects of fossil CO_2 emissions occur in the first 300 years after release, but the cumulative mean lifetime effect of fossil fuel CO_2 is 30 000 years [4] (figure 1). Thus, the effects of CO_2 release can be considered in geological timescales, as is the case for radioactive wastes. In human timescale terms, these effects last longer than the entire history of the *sapiens* species. This emissions effect could be conceptualized as 'The first 50% drives global change (i.e. peak warming within decades); the last 25% lasts forever (i.e. a tail out warming effect through tens thousands of years)'. After the 2015 Paris UNFCCC agreement to aspire to a maximum 1.5°C warming, and a firm commitment to stay well below 2°C, it is unclear how to deliver emissions reductions to meet these targets [5]. Many institutions affect climate policy, but unlike the oceans, the Earth's atmosphere has no direct or dedicated treaty to protect its abuse. Who will protect the atmosphere?

Three options exist for humanity related to climate change: (i) do nothing, and await practical consequences beyond any doubt, (ii) develop and deploy engineering technologies to increase reflectance of solar radiation, (iii) reduce the rate of CO_2 emission and recapture large quantities of CO_2 already emitted. This article explores the third option, and examines potential techniques with the largest impact (figure 2). A particular focus is technologies that rely on engineered CO_2 storage in subsurface geological reservoirs (CCS). The IEA and others persistently calculate that engineered CCS will be required to contribute 15–20% of global CO_2 emissions reduction by 2050, i.e. at a rate of 6000 Mt CO_2 yr^{-1} [6]. Although climate modelling, and projections of future mitigation, can easily switch on or switch off the deployment of different options, experience in the real world shows that regulation, politics, locking-in to existing systems and finance, all conspire to slow down, and prevent, technological mitigation actions. It is also important to be aware that discussion of CCS development and deployment has direct implications to the future feasibility of negative emission technologies (NETs), including CO_2 recapture. Many elements

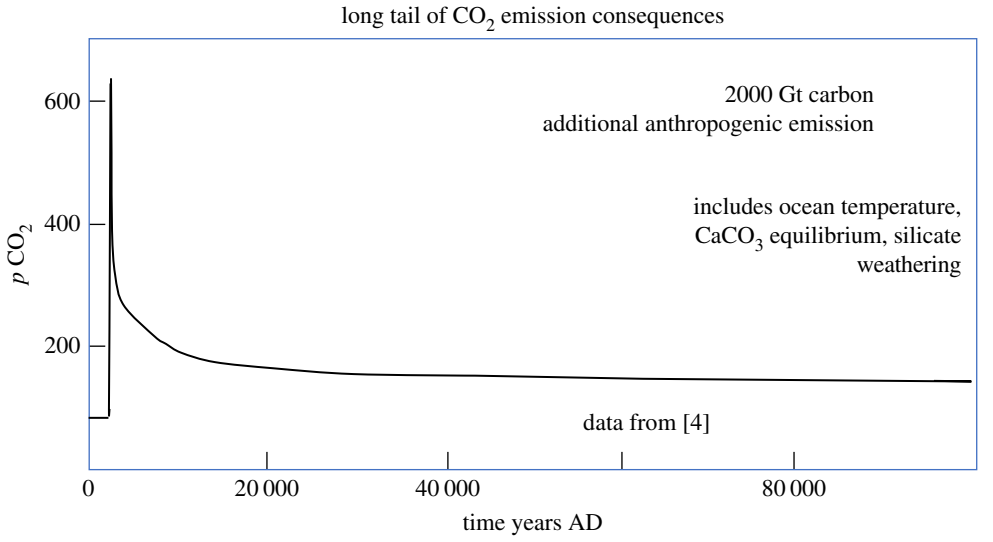

Figure 1. CO_2 emissions to global atmosphere increase rapidly and drive global changes of sea-level rise, ocean acidification and warming. Atmospheric CO_2 has a long residence time, and decay of atmospheric concentrations are slow, with direct effects still apparent for 30 000–100 000 years. (Online version in colour.)

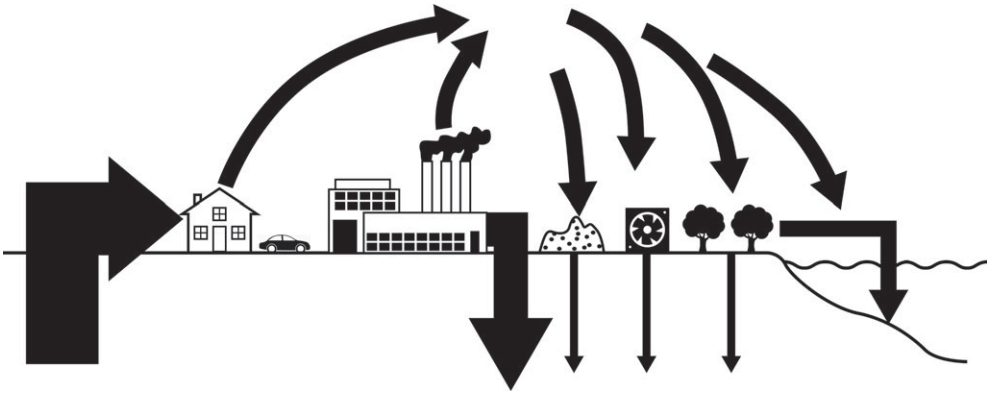

Figure 2. Conceptual pathways of anthropogenic carbon flows to be managed. Reading from the left: vast tonnages of carbon from coal, oil and gas are geologically extracted from fossil sources and modern biomass. Combustion and conversion in houses, businesses, transport and industries produce emissions to atmosphere which can be greatly reduced by CCS. Capture and storage enables injection direct from industrial sites for secure long-duration storage in the very deep subsurface. Already emitted CO_2 in the atmosphere and diffuse or small sources can be recaptured by NETs, such as enhanced weathering, DAC, BECCS, enhancing natural ocean dissolution and direct ocean injection.

of the latter are dependent on the ability at international scale to (re)capture and store CO_2. Thus, bioenergy and CCS (BECCS) and direct air capture (DAC) are dependent on the global development of CCS.

An example of the mismatch between implementation of CCS and BECCS in emissions mitigation models and reality is in the IPCC AR5 [7] models that project forward in time from the present day (or in this case 2014) to the year 2100. In fig. SPM1 of [7], total anthropogenic GHG emissions in 2010 (starting conditions) were 49 ± 4.5 Gt CO_2 eq yr^{-1}, of which 38 ± 3.8 Gt CO_2 eq yr^{-1} were from energy and industry. For mitigation pathways into the future, success is

defined as likely (66–100%) if a global temperature increase will be less than 2°C, i.e. a maximum atmospheric CO_2 eq of 450 ppm is limited by 2100. Modelling in IPCC AR5 investigated the effect of CCS and BECCS, or the impact of no CCS. Modelling included 31 models and 1184 scenarios. Results in fig. SPM7 of [7] draw upon 147 baseline scenarios of low carbon energy systems, although we note that there is no clear information on how many scenarios were not fully run or failed to finish. Results in IPCC AR5 SYR SPM table SPM2 of [8] show that the success and economic impacts of avoiding CCS are large. Without CCS, only four scenarios maintained 450 ppm or less by 2100, those four were fewer than half of the scenarios run, and produced a modal 138% increase of mitigation cost (up to 297% extra cost). To maintain less than 550 ppm by 2100, 11 scenarios were run with no CCS and all were successful, but with a modal cost increase of 39% (maximum 78% additional cost). These complex results were summarized in a statement from IPCC AR5 that 'many models cannot reach about 450 ppm CO_2 eq concentration by 2100 in the absence of CCS'. It is not reported by IPCC what conditions models used to achieve success. For the IEA model, often taken as an international benchmark, we do know that embedded assumptions to achieve rapid and optimized implementation of CCS include a globally compelling carbon price, with no lead-in time for countries to assess storage, or develop regulatory or commercial incentives. We consider that these are unrealistic positive assumptions, which underplay the difficulty of developing CCS rapidly. Large political, regulatory, business and technological changes for CCS, BECCS or NET are needed. These changes are well understood, but now require action sustained through decades.

Simulations for RCP2.6 which represent a future global rise of 2°C or less, all required CCS as well as 40–220 Gt of NET. This was predominantly represented in IPCC modelling as delivered via BECCS. By contrast, only a few simulations without CCS (36% of those reported) succeeded in remaining below 2°C. Inclusion of (BE)CCS created 'feasible' 2°C model pathways, but ignored the unreality that BECCS is barely deployed at industrial scale; at present, the only BECCS system functioning at a suitably large scale (approx. 1 Mt $CO_2\,yr^{-1}$) is the Illinois Industrial CCS fermentation plant at Decatur, Illinois [9]. BECCS by combustion has not been developed commercially and BECCS by gasification has barely been trialled. At least a decade of development can be expected, followed by decades of build-out to achieve global impact.

Although technically operational, due to delayed delivery, the CCS group of technologies will have limited impact on retaining global warming below 1.5°C in the 10–20 year timescale towards the 2040s. By contrast, this group of technologies is capable of greatly assisting in achieving the difference between 2°C and more than 4.5°C warming which will occur by 2100 if mitigation actions are not taken. If CCS is ignored, and the development pathway is not commenced immediately, then improved efficiency of capture technologies will not undergo cycles of learning and optimization; networks to transport CO_2 from capture to storage sites will not be planned and built; and an efficient market to accept CO_2 storage will not be evolved [10,11].

It is apparent that human political systems are poorly constructed to undertake large and fundamental changes affecting the future, when the evidence presented is intellectual and scientific, rather than directly experiential and personal, or when experiences do not impart a significant personal impact. One well-studied example of this conservatism is a study in a small Norwegian community (a country leading in CCS and familiar with low carbon energy), showing that although changing weather and seasons are logically believed to be caused by climate change and human industrial activities, that does not lead to actions to change behaviours [12]. Societal structures are reluctant to rapidly change from the lock-in of energy systems founded on convenient, widely available and low-cost fossil carbon and biocarbon, which have no penalties against waste disposal of CO_2 into the atmosphere. The projected effects may be catastrophic, but are not compelling in their immediacy and may be geographically and socially distant from the populations that can have the greatest impact by taking mitigating action. With an accumulation of evidence globally, and in the USA from flooding in New Orleans, New York and Houston—the question is changing from 'did climate cause this event' to 'does climate change make this event more likely to occur or greater in its impact?' That slow change of thought to attribute extreme

weather probability and impact to climate change [13] may eventually produce positive answers to the question 'Why spend more now to help generations into the future, to reduce a problem which may or may not happen?'

The construct and framing of the CCS technology family from the mid-1990s has been explained in terms of large-scale actions to address failures of environmental accounting in the energy system. This has not worked, even when evidenced and supported by numerous predictions of the future, simulations and economic calculations made by established and expert authorities (IPCC, Royal Society, UK Committee on Climate Change, IEA, US Department of Energy). We infer that the problem of climate is not simply scientific or technical; it is seemingly not simple enough, and not directly linked enough to immediate priorities, to initiate action from consumers, citizens or voters across populous and economically powerful nations [14].

Nevertheless, we assert that fundamental actions will become necessary, and will be perceived to be so, before the 2030s. Rather than persistently advocating large and expensive funding from indebted governments, we here explain some of the steps required on a development pathway for the CCS group of technologies. Those steps rely first on the national identification of CO_2 storage options, which vary greatly between countries. Realistic and serious engagement with carbon storage options, now, followed by undertaking strategic storage evaluation at a low-cost to a national budget, will describe and locate the individual assets local to, and particular to, a country. That informs decisions to construct or buy in CO_2 capture equipment from the global market during late 2020s onwards. However, reducing emissions rapidly from electricity production, or even reducing emissions slowly from across a whole economy does not balance with the continued extraction and release of fossil carbon. To decrease all-economy emissions by 3%, compounded year after year, requires rapid and verifiable actions which persist for the duration of industrial investments. Elaborate mechanisms of trading emissions permits, or international offsetting, have failed to incentivize real and verifiable storage of CO_2. For example, the world's largest carbon pricing mechanism, the EU Emissions Trading Scheme (EU-ETS) has not functionally supported CCS development as a mitigation technology. The EU-ETS allows continued CO_2 emissions, through an increasing price of permits for each tonne of CO_2; thus lack-of-emissions saves money, but storage is not encouraged. Even tax credits bestowed in the USA explicitly to incentivize use of CO_2 in enhanced oil recovery, do not require verifiable storage of CO_2, just its short-term utilization as a fluid to assist in oil production. We suggest that political and regulatory adaptations should be linked directly to create at least equal value between emissions reduction and the desired outcome of CO_2 storage, in order that storage can be achieved rapidly and with minimum oversight. One example of a simple and direct linkage has been the Norwegian tax on offshore hydrocarbon production emissions of GHGs [15] this resulted in a direct action to capture, inject and store CO_2. This type of tax could easily and rapidly be replicated worldwide to reduce associated emissions from hydrocarbon production. As discussed later, we favour a conceptually simple but powerful Certificate of Storage, awarded to extractors of fossil carbon, which mandates the requirement to store a decreed equivalent percentage of the fossil carbon produced. Low-cost actions taken now can create valuable and diverse options in 10 years time to invest in, build, and operate CO_2 capture equipment, thereby supplying CO_2 for storage. Value creation is more important than cost reduction.

2. CO_2 reduction for 1.5°C, focusing on electricity, energy or emissions?

We start with CCS as it persistently features in government and research analysis. And as the most developed of all CO_2 reduction technologies it is the most suited to imminent deployment. We suggest that in doing so, the following two features of CCS need to be fully appreciated.

First, CCS is not restricted only to electricity generation. In an economy where fossil fuel use is pervasive, reduction of emissions through CCS can be applied to: (i) upstream removal of associated CO_2 produced together with oil or especially gas, (ii) electricity generation from oil, coal or gas, (iii) fuel and process emissions from large industries, (iv) supply of heat to domestic and industrial users, (v) conversion, and especially combustion, of modern biomass for

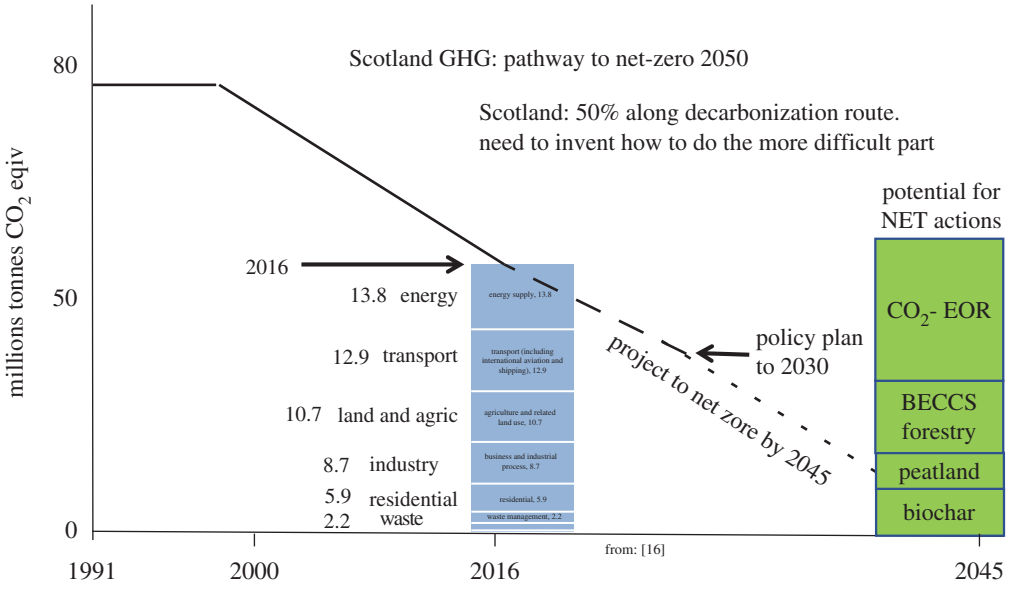

Figure 3. Pathway of greenhouse gas reduction beyond decarbonized electricity in Scotland [16]. About half of CO_2 equivalent emissions have been reduced by closure or modernization of old industries. The remainder includes emitters not closely connected to energy. Instead of decarbonizing all emitters at great expense, it could be viable to offset emissions by NET, to achieve net-zero by mid-century. A blend of reduced new emissions, plus recaptured existing emissions with NET is likely to be lower cost than requiring capture of all emissions, which becomes exponentially expensive. For example, the recapture of biomass CO_2 using CCS is modelled by TIMES/MARKAL to be a least-cost option for the energy whole-system in Scotland from 2027 [17]. CO_2-enhanced oil recovery (EOR) is included, because Scotland is currently an oil producer, but could choose to balance that carbon extraction by increased CO_2 injection [18]. Using the option of CO_2-EOR requires more government monitoring through a multi-decade timescale making the regulation of Certificates of Storage more complex.

heat or feedstock, and (vi) replacement of hydrocarbon fuel in surface transport with electricity or hydrogen. Consequently, it has been an historic mistake for developed industrial economies to over-focus on the application of CCS to electricity generation from coal with some attention to gas. This has pitched the final product of decarbonized electricity into a market where subsidized renewable generation can produce electricity at prices comparable to or cheaper than conventional high carbon power. CCS then fails commercially. The true value of CCS is its ability to be applied across the entire economy.

Second, that achieving a national and global balance for greenhouse gas emissions (net-zero balance), either by mid-century, or much more urgently to limit temperature rise above 1.5°C, requires more than just attention to energy, and more than just attention to decarbonization. This is a fundamental all-economy inventory, which has not yet been widely and comprehensively realized (figure 3).

Here, we cite the example of Scotland: a small industrial country with a large ambition to be a leader in climate action. Scotland has seen closure of many large legacy industries from coal burning and industrialization. Thus Scotland forms an example of where many industrial economies may find themselves in the mid-to-late 2020s once 'easy' actions of high carbon closure have been taken. What is left to do? Figure 3 shows that great progress has been made since 1990 by reducing emissions of fossil carbon in the energy sector. However, to make further progress towards zero emissions requires actions on greenhouse gas sources such as agricultural land use, refrigerants and industrial process emissions. Although reducing emissions from energy is a crucial first step, most industrial economies typically emit 30% of greenhouse gases from non-energy sources.

3. CCS: group of technologies

CCS is a group of technologies, which have the common aim to reduce greenhouse gas emissions to atmosphere from the extraction, combustion or utilization of fossil fuels and carbon-containing resources [19]. This provides a means whereby widespread, accessible, portable and dense energy storage fuels may be used with minimal impact to the climate. These fossil fuels have been the basis for industrialization and energy production since the mid-1600 s, and are the foundation for wealth creation at the present day in industrial countries. Fossil fuels are easy to extract and use, and, as the common global atmosphere is not protected by any global treaty that penalizes the release of greenhouse gases, there is no direct financial cost internalized to users of fossil fuel-derived energy services. This giant legal loophole has enabled unchecked and runaway exploitation of fossil fuels, which in 2017 still provide 80% of global energy, in spite of widely recognized and agreed adverse environmental consequences. CCS is typically considered as three independent yet inter-connected steps: (i) the separation and purification of CO_2 from fuels, feedstocks and industrial processes, (ii) the compression and transport of CO_2 by pipeline or tanker to its storage destination, (iii) injection of CO_2 through an oilfield style borehole into microscopic pore space of geological reservoirs of the deep subsurface, where the CO_2 will remain in perpetuity. CCS development and frontier issues are discussed in [20,21].

Purposeful capture of CO_2 and storage for atmosphere protection was proposed many decades ago by Marchetti in 1977 [22]. In the present discussion of technologies to reduce emissions and to achieve negative emissions, the importance of CCS with geological storage is that it is flexible in application to diverse CO_2 sources, has a long history of industrial development compared to NETs, and several industrial scale projects have been operating for over 20 years. CCS has a unique role in creating the storage destination for negative emission technologies such as BECCS and DAC. There is much focus on the technologies of gas separation or CO_2 capture, but much less consideration of where the captured CO_2 will be stored or disposed, how that will be done, who will enact that and who will pay for it. If CCS is not developed and deployed, and methods discovered to enable financing or create mandates for organizations to undertake CO_2 capture, transport and especially storage, then the ability to undertake BECCS does not exist and the ability to undertake geological storage of CO_2 derived from DAC does not exist. CCS is an essential entry point for all types of geological CO_2 storage.

Many techno-economic analyses have been compiled to show that CCS, acting across a whole economy, is clearly beneficial on a cost basis, reducing the cost of decarbonization by a factor of 2.5 compared to more radical activities needed if CCS is not deployed on many applications (IPCC AR5 2014). Emissions reductions through CCS and the ability to achieve negative emissions in the national energy system is modelled by the UK Energy Technologies Institute as essential. Omitting either biomass or CCS would double the cost of meeting climate change targets to more than 2% of GDP, and omitting both would mean that targets could not be met at all [23]. Modelling across the whole energy system across 10 States of the European Union shows that CCS has particular application to Combined Heat and Power, to steel, cement, oil and gas, and to heat delivery via hydrogen [24]. CCS can reduce present emissions by 70% and be a cost saving of €1 Trillion by 2050, providing a sustained annual benefit of €50 Billion thereafter [24]. The problem is enabling the entry and growth of a new clean emissions technology, which appears to be more expensive than the incumbent familiar methods. Countries in Europe, North America and Australia have attempted to make this change through retrofitting coal-fuelled power plants. That has not worked, because the rise of renewable energies has provided alternative sources for low carbon electricity, which have been heavily subsidized, and have also shown very rapid cost reductions as a consequence of multiple and rapid build cycles. In many parts of the world, a new coal plant is now more expensive than the equivalent power generation from onshore wind or photovoltaics [25]; and that is without the additional expense of fitting CO_2 capture and developing transport with storage. CCS on electricity has not gone through enough learning cycles to achieve cost reduction, and currently appears overly expensive to build.

CCS on coal may still have a role if there are local reasons to install CCS as protection for the option to use local, or reliably imported, low-cost fuel sources—such as at Boundary Dam Saskatchewan, or Petra Nova, Texas. For administrations with diverse options for electricity supply (e.g. the UK, the Netherlands, California or Alberta), the price of CCS on coal power plants has helped the phase out of coal-use sooner than expected—new build electricity is gas powered or renewable. Thus, market-based choices have decarbonized by a different method. The failure of 'clean coal' is undoubtedly a problem in terms of immediate CCS deployment to produce a RCP 2.6 pathway as modelled by the IPCC. In practice for CCS, the years from 1994 to 2005 produced a gradual invention of theory: legal and regulatory systems, assessing CO_2 storage and conceptualizing projects. The years 2005–2015 were lost in trying to build giant scale projects, unsuccessful because no compelling financial case existed. To progress from subsidized pilot projects to commercial operation, we suggest that a different framing is needed to position CCS more correctly as an 'atmosphere protection, and clean air health benefit', and CCS should be a required licence to operate if businesses wish to work with fossil carbon.

We next consider the early implementation of CCS technologies and discuss the enabling factors already in place, and those that need to be adapted or created, for CCS to develop. CO_2-EOR has emerged as the only commercial method to incentivize CCS, and most CO_2 storage (in 2018 totalling 60 Mt CO_2 each year) currently works through such projects (electronic supplementary material). Although many current CO_2-EOR projects derive CO_2 from natural volcanic sources, it is clear that CO_2-EOR can, and does, operate successfully as the destination for CO_2 which has been captured from anthropogenic emissions—for example CO_2 captured at Petra Nova and Boundary Dam power plants is sold to oil companies for use in CO_2-EOR. These are self-starting, commercially viable projects, which purchase CO_2 at $20–40 per tonne and can be incentivized by additional tax allowances (as in Texas) or a low carbon price. (However, present regulations focus on enabling production of additional oil, rather than ensuring storage of CO_2. There is no requirement in the USA to monitor CO_2-EOR projects against CO_2 leakage beyond the performance of the injection well itself. But where detailed investigations have been made, no leaks have been detected, even though hundreds of legacy boreholes exist [26]. Additionally, CO_2-EOR greatly increases the quantity of CO_2 which dissolves into reservoir porewater, so that storage is more secure than physical retention by top seal mudrocks in an aquifer store [27]. To avoid future EOR projects increasing CO_2 emissions by additional oil production, environmental regulations need to be applied to ensure that CO_2 injection continues after the oil has been extracted. Such regulation could ensure that EOR projects store more carbon than they produce through their duration. The initial oil production phase is carbon positive and makes enough money to avoid public subsidy for the infrastructure necessary to achieve the subsequent carbon negative phase [18]. Through multiple build cycles, at minimal public subsidy cost, CO_2-EOR can be a way to rapidly develop low-cost CO_2 capture and separation processes, and the fastest way to develop many tens of millions of tonnes per year CO_2 storage. If regulated for CO_2 storage, an EOR route could create a market to purchase and store immense quantities of CO_2. One study by the US Department of Energy cites an additional 240 Bn bbl recoverable unrisked oil resource. CO_2-EOR is currently the largest utilization of CO_2, and would remain so. A risk is weak regulation, where governments encourage CO_2-EOR, but fail to enforce continued injection of CO_2 to balance carbon emissions after oil production has ceased.

Utilization of CO_2 (CCUS) is discussed as a method of commercially valuing CO_2 and creating a sale price which can recover the costs of CO_2 capture. The attraction is clear, instead of paying to capture CO_2 and paying to store CO_2, that same gas stream can be used, sometimes untreated, as a reagent to create saleable products. About 114 Mt CO_2 per year were used globally in 2012 for utilization which was not EOR—such as chemical reagents in water treatment or urea making [28]. Utilization can have four benefits: reduction of net emissions; making money; meaningful scale; and long-duration storage of CO_2. The key to all of these is a wide ranging end-to-end full life cycle analysis, focused on carbon accounting. Because of the low energy state of CO_2, it is not surprising that CO_2 is not widely used as a chemical reagent. Energy needs to

be input directly, or by associated reactions, to transform CO_2 into different compounds. For that reason the additional energy sources need to be properly accounted for in such carbon emission calculations. The tonnage of material manufactured has to be compared to the existing or future demand—one power plant emitting 2 Mt CO_2 yr^{-1} could in principle over-supply the world demand for aspirin made from its CO_2. The 6 Bt CO_2 yr^{-1} required to be stored by 2050 greatly exceed the demand for manufactured carbon products (except possibly for carbon recycled from air for fuel, see below). And the duration of storage is essential to understand. An established commercial use of CO_2 is to enhance horticulture in greenhouses. Yet the larger tomatoes grown will contain CO_2 for a period of only weeks, before being consumed and the CO_2 re-emitted. All CCUS propositions should be compared to the hundreds to thousands of years required for storage to be maintained (figure 1).

The life cycle is sometimes hard to assess—as each actor along the chain can gain a benefit in their narrow view, yet the overall global emissions for climate see no benefit, and often are worse than with no CCUS. A real example is described here, starting with the capture of CO_2 from a coal power plant, using a greatly improved solvent (but still requiring extra energy). The solvent makers are happy because they sell their product, the coal plant operators are happy because some of their CO_2 is captured. The captured CO_2 is converted (using extra energy) to a saleable chemical which is locally in short supply and is currently imported. A new local supply is welcomed by government (reducing imports) and by the user (less cost). The chemical is used—as a flux in glass making to produce cheaper glass, but within that flux process the chemical becomes a reagent and CO_2 is emitted as a gas to atmosphere. All actors along the chain are making money, and some claim to be reducing emissions—especially through more efficient capture at a power plant. But the overall effect is to increase emissions to atmosphere due to higher energy requirements. While there are benefits to developing CCUS, it seems unlikely to achieve the scale or authentic emissions reductions required. CCUS is a way of making money, but not a straightforward way of storing CO_2 for long timespans.

4. Examining CCS, to predict progress

(a) CCS history: past projects

What is the history of CCS project development, and what are the possibilities that CCS projects will match the requirements modelled by IPCC and others to place the world onto a sustainable RCP 2.6 pathway? Scott 2013 [29] made a high-level aggregated analysis to show that the development of CCS to 2014 was lagging behind IEA projections by a factor of 10. Now in 2017, CCS projects are still few in number, so that it is possible to assemble all the data for all the projects worldwide to understand the past as a guide to the future development rate. We have undertaken this rigorously, for the first time, using the public databases from GCCSI (a membership organization promoting CCS development) and from SCCS (an academic university group, funded by government) which are independent of each other (electronic supplementary material). During this compilation we have cross checked the data from the two tables. In all cases, the essential numbers are a good match, with differences ascribed only to rounding errors or simplistic reporting in the media. Consequently, we assume that these data are accurate and reliable. These databases have been translated into a tabulation, from where we can assess the project, date of commencement, date of operation commenced, technologies and purpose of the project and tonnage of CO_2 stored per year (electronic supplementary material).

The track record of projects appears clear. CCS technology operating at large-scale has existed since the 1970s. Government supported projects to help develop and commercialize capture have been predominantly focused around electricity generation. The great majority of CO_2 injection is linked to projects of enhanced oil recovery in the USA, which provides additional income (electronic supplementary material).

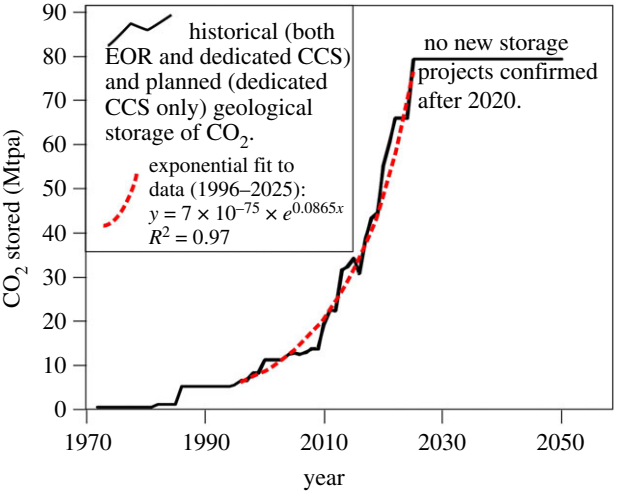

Figure 4. Compilation of past and current CCS projects at industrial size, showing continual increase to present day, but at a rate much slower than planned or politically pledged. For example, the UK pledged four projects, the EU 'up to 12' and the G8 pledged 20 projects. About four commercial-scale projects are operating in total—all in North America. After 2022, research may continue, but a global expiration of grant funding on demonstration projects means that no new CCS is presently scheduled to commence. Governments with existing support for CCS now need to take action by creating CO_2 storage markets (not emissions markets) or by taxing of specific CO_2 emissions, to enable these successful demonstration projects to be reproduced in much greater numbers. Governments worldwide, need to commence analysis and regulation for their CO_2 storage, CCS infrastructure and development.

(b) CCS outlook, immediate and medium future

A display of projects through time (electronic supplementary material) shows an increase in build rate and in size of the project constructed from 2005 to 2017. Projects capturing CO_2, and selling that to enhanced oil recovery operations in the USA are clearly much more successful than those projects on power alone, or an industry which is not able to access CO_2 sales through an EOR market. All industry and power projects which do not have an EOR market, and are undertaking 'pure' CO_2 CCS for environmental purposes, rely on subsidies. Funding for research is set to continue in Europe and the USA for the short term. Contrasting with that is a limited grouping of industrial scale projects which has emerged through subsidy, particularly in the USA, and also includes CO_2 capture from process and point source industries. However, the operational subsidies for current development programmes, in the USA and elsewhere, are scheduled to expire in the very early 2020s [30,31]. Beyond that date, no new commercial sized CCS projects are scheduled for support (figure 4). If policy or financing action is not taken, then the pipeline of new build CCS projects globally will cease operation, and no new progress will be made after the early 2020s. To remedy this, future projects will continue to need underpinning by subsidy, or CO_2 storage must be mandated by Certificates, or made more financially viable by instruments such as targeted taxes on emissions.

Our new examination of the rate of past project growth, expressed as mass of CO_2 captured per year, allows a very good fit to an exponential trend line (figure 4) with a reasonable statistical confidence ($R^2 = 0.97$). Assuming that multiple other countries worldwide will adopt funding incentives to get projects built at a similar level to the last decade by US DoE, we extrapolate this historic exponential trend of CO_2 storage into the future and predict that yearly storage will be only 700 Mt CO_2 by 2050 (figure 4*a*). That compares extremely badly against the IEA projection of 6000 Mt CO_2 yr^{-1} necessary [2] to reach a 2°C sustainable climate (figure 4*b*). The IEA trend is usually derived from assumptions about continued need and growth of energy services amongst members, and an assumption that carbon taxes will be introduced across developed economies,

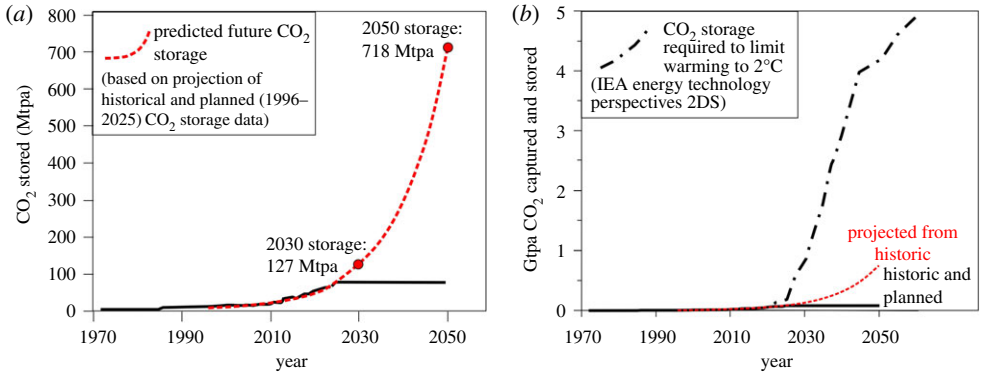

Figure 5. (*a*) Extrapolation of build rate and CO_2 capture rate from the 1990s shows that CCS could readily continue rapid growth, if existing countries provide incentives, and if new countries start to deploy CCS. However, that projection predicts only 700 Mt CO_2 yr^{-1} disposal by 2050. (*b*) By contrast, a 2°C sustainable path from IEA requires 6000 Mt CO_2 yr^{-1} to be stored. Extrapolation of sustained growth in capture projects (not shown) shows that 6000 Mt CO_2 yr^{-1} could be achieved in 2110, i.e. a very delayed arrival. Future CO_2 capture extrapolated from the exponential fit in figure 4.

and then globally, to ensure that CCS is better than emitting unabated flue or process gases. Figure 5 projection can be seen as either a 'fail' to be able to reach CO_2 storage targets by 2050. Or this can be seen as a 'delayed arrival' at the CO_2 target of 6000 Mt CO_2 yr^{-1} in 2110. Extrapolating from this graph suggests that CCS requires continued rapid growth of installation now, with uninterrupted increased growth from mid-2020s to 2050, and linear growth to 2110. The predictions made by Scott *et al.* in 2013 [29] are surviving well. These show a slow pace of CCS development, and do not include NET or DAC.

5. Re-framing CCS: what could be done to change the narrative?

(a) How long has this taken?

Limiting to 1.5°C is difficult, especially in the timescale of 10–20 years. Many NET are conceptualized, but are not tested beyond pilot scale. These NET need to be made ready to deploy before a 2°C warming target is breached, and the example demonstrated here from CCS shows that an interlocking set of enabling actions needs to be created by countries; just inventing a technology is not enough. The only technology group to have equipment operating at commercial scale is CCS, but this still relies on subsidy-driven developments, and has not achieved cost-reduction or been adopted as standard practice. That has taken 40 years since the concept was first published, 45 years since CO_2 was first deliberately injected into geological oil reservoirs, 27 years since the first research was undertaken on a CCS system, and 13 years since 2005, when G8 political heads of state at Gleneagles declared CCS to be a priority against climate change. Yet, as IPCC AR5 modelling showed in 2014, CCS is by far the most impactful technology group, without which it is difficult to find alternative methods of staying within a 2°C warming target. CCS also enables some of the simplest NET (BECCS) and the most fundamental NET (DAC) to be enacted. Large technologies typically take two or three decades to move from invention, test-bed, pilot and demonstration, to commercial operation—and then rapid build rates to achieve 'materiality' of at least 10% of the anticipated capacity installed worldwide.

(b) Creating incentives: Certificates of Storage

Emissions trading in Europe has failed [32] to develop CCS projects, or to incentivize CO_2 storage because the EU-ETS permits are needed to emit, not to store, and because the traded price of permits is far too low, volatile and uncertain into the future to produce CCS investment in

very large power or industrial projects. To develop a new technology application, such as CCS, a high level of subsidy with a prolonged time duration is needed. This is exemplified by the USA DoE three-stage planning to pull through technology emergence. Europe tried a version of special funding with the New Entrants Reserve, intended for individual CCS projects. However, the complexity of co-funding and competition from renewables resulted in no progress. A new innovation fund may emerge from a modified EU-ETS in Europe to fund industry projects in the 2020s. However, a moderately stronger EU-ETS price during the 2020s spreading across the whole economy will not work. Predictions that the permits will increase from €5 per tonne to €30 per tonne CO_2 is far away from the €80–100/tonne costs required to fund a CCS project on industry or electricity.

Achieving large numbers of global installations also assumes that the technology is wanted, either in a sense of lower cost, or in achieving a necessary or mandated objective. Neither of these are really true for CCS. It can be claimed that CCS provides a necessary service of atmosphere protection against excess CO_2 but that is not generally agreed in a legal sense of binding agreements and targets. Most CCS operations are more expensive than not undertaking CCS. To deploy CCS at scale one of the following is needed: (i) adjustments to prices of fossil fuels, (ii) greater penalties or taxes for emissions, or (iii) simply a mandated set of targets for fossil fuel owners or greenhouse gas emitters. Haszeldine [33] suggested a simple concept which could be enacted that fossil fuel producers or importers are each year required to store an increasing percentage of the emissions which their products cause. The carbon producer takes liability for clean-up, not the end user. A market and mandate for carbon storage is created, which is currently missing in all climate actions, where emissions are priced or traded. Certificates of Storage could impart an obligation to verifiably store emissions equivalent to a percentage of fossil carbon extracted or imported. This action can start small, then predictably increases (e.g. at a compounded 3% yr^{-1}) to the required level by mid-century. Liability for long-term CO_2 ownership, and security of storage performance can only be held by governments, not companies. This liability for leakage is calculated to be very small.

(c) Where to apply CCS: hydrocarbon production, industry, biomass

How can CCS be started, and how can learning be gained, costs reduced, infrastructure for transport and storage be built? Are there places to start, not by targeting victim industries who 'have to' develop CCS, but at points of least resistance, where high-concentration CO_2 already exists, where infrastructure facilities or skills already exist, or where the 'permission to continue to operate' with fossil carbon can be progressively introduced?

Separation of CO_2 gas from hydrocarbons has been an industrial process since the 1920s and operates daily in both the production of natural methane gas and hydrogen production in refineries worldwide. Commercial standards for selling gas or other hydrocarbons usually require a pipeline with less than 1 or 2% CO_2. So 'acid gases' like CO_2, or SO_2 in other regions, are routinely separated before the hydrocarbon is sold and pipelined away from a gas field. These operations by hydrocarbon companies are well established, and form the basis of worldwide projects such as Sleipner, Snøhvit, In Salah and Gorgon. The difference is that SO_2 is re-injected for disposal, as it is classified as a hazardous gas, whereas most CO_2 separated is vented to atmosphere, as a pure gas, because there is minimal or no penalty. The four projects listed above are CCS projects, because there is a targeted local tax on CO_2 emission or because the operating company has elected to store the CO_2 for self-decided environmental purposes. Here is a clear and simple way to start large-scale CO_2 storage worldwide: locally tax CO_2 emissions from 'associated gases'. This will encourage a market decision by the operating company, to use their expertise, to drill a borehole, inject and monitor the CO_2.

Similar logic applies to emissions from industry. There are many sources of high-concentration CO_2—from fermentation, ammonia manufacture, fertilizer manufacture, hydrocarbon reforming to make hydrogen, cement making and from some iron and steel processes. These streams of high-concentration CO_2 are routinely vented. But if emissions are locally taxed, then the industries will

seek least-cost remedies. This situation is more commercially complex than for associated gases, because the large chemical and process industries claim that their market is ultra-competitive and any price increase on their product is not possible. However, it is not insoluble, governments can and do apply correcting trade tariffs on environmental grounds, like many imports into the EU.

As attention starts to move from decarbonizing electricity onto decarbonizing heat and transport, then the role of hydrogen is emerging as an energy vector for heat and for fuel cell vehicles [34]. Hydrogen can immediately be made at least cost from steam reformers of methane, in well-established industrial processes, which produce easily separable CO_2 as a by-product. This may also act as an early entry point for low-cost CO_2 transport and storage.

(d) Creating a transport and storage infrastructure

Using CCS across a whole energy system is persistently modelled as a least-cost decarbonization option. That whole-system benefit is currently blocked because it is clear that individual large commercial-scale CCS projects on power or on industry have large capital costs, feed into unclear markets where renewable electricity or heat can be subsidized at lower prices, and have cross-party business risks between capture, transport and storage. This is difficult for a single industry to take on, especially as the first projects combine the expense and risk of building and operating CO_2 capture, with the very different skills and risks of developing a transport system and a robust storage site. The UK has tried three times since 2005 to develop those three items together and has failed each time on costs and risks.

It is necessary to disentangle these three different components of a CCS system. To service CCS projects—especially for industry, it may be necessary for Government to assist in creation of a 'CO_2 takeaway service'. This can be achieved by leading the planning, construction and initial operation of pipeline and storage networks, into which industry can feed its CO_2 at minimum cost. Once operating, the initial network can be sold. This is the conclusion of independent analyses in Europe by the Zero Emissions Platform advising the European Government [35], by the Oxburgh Parliamentary Advisory Group [36] to the UK Government and by the Norwegian Government creating GassCo as part of Gassnova to be a state operated company. In the latter, GassCo will supervise CO_2 transport by pipe or shipping as part of the first full-scale offshore CCS project [37]. The first actions are needed now as it is apparent from EU, USA, Canada and Australia experiences that up to 10 years is needed to evaluate commercial storage and introduce enabling legislation. That 10 year lead-in time can create the first trials of injection, and at present is followed by another 5–10 years of operation before scaling up.

6. Beyond CCS to NET

Many technological and behavioural actions are available to reduce carbon emissions. It is clear that following the pioneering work of Lovins in the Rocky Mountain Institute that deep and designed efficiency improvements can reduce energy consumption, and hence emissions, by up to 40% within one to two decades [38]. However, historical pathways show that these actions, however, logical, are unlikely to be deployed sufficiently rapidly to meet a 1.5°C warming limit within 10 or 20 years. Actions to reduce emissions, exemplified by CCS, are discussed above, but require significant additional investment in very large equipment. At present this implies reductions in efficiency of fuel use, and so is unlikely to be deployed in a 20 year timescale unless fundamental changes of financing and taxation are made.

There are possibilities available to recapture and securely store carbon which has already been emitted into the atmosphere or ocean. In addition, there are possibilities to recapture carbon which has already been used, and recycle that carbon into productive use. This will reduce and eventually eliminate the need to extract additional fossil carbon from commercial geological reserves. Such actions are grouped under negative emission technologies (NET) or carbon dioxide removal (CDR).

A large number of NET are potentially available (figure 6) but none has yet been proven at commercial scale. Equally, none have been proposed in a framework which permits conventional finance or incumbent economic realism to promote their widespread development and operation. A discussion of the different technology options is briefly developed below, with particular attention to the potential size and impact on the scale of problem, the present-day cost and potential future cost, and the reliability and timescale on which CO_2 or other greenhouse gases are stored.

7. CCS and NET

(a) The range of possibility

Comprehensive examinations of NET have been made by several meta studies [39–42]. These studies identify some 5–10 different activities which could be considered as reliable methods of NET. When considering the practical enactment for any of these, Scott *et al.* 2015 [1] identified several parameters which need to be considered. These include (i) the potential global impact, i.e. how much carbon per year could an individual technology accept; (ii) security of storage, i.e. how reliable is that carbon storage for the next 1000–10 000 years required for the Earth's self-regulating systems to re-equilibrate; (iii) maintenance, i.e. how much effort and attention and expenditure needs to be input so that carbon storage performance remains secure and can be demonstrated as secure; (iv) technological feasibility at scale, i.e. can these be built now at sizes 0.1–0.3 of the designed optimum size so that scale up to high-impact operations could be envisaged within 10–20 years; (v) energy efficiency, i.e. can these processes and technologies work efficiently, bearing in mind that extracting CO_2 from air at 400 ppm will in conventional process engineering use more energy than extracting CO_2 from flue gas at 120 000 ppm, so that novel methods of operating which consume minimal additional energy need to be invented; (vi) the cost, although some methods are more developed, and others merely experiments or ideas, can a pathway be foreseen to compete with, or be cheaper than, engineered geological CCS?

If fossil or biological carbon is used and released or recaptured by any of the NET, then that equivalent amount of additional CO_2 storage is required to maintain an accounting balance. The global sinks available for long-duration CO_2 storage are few, the capacities are poorly known, and are subject to large uncertainty in engineered efficiency of use, politics and commercial availability. These are diagrammatically summarized in figure 6.

Scott *et al.* [1] identified 10 different methods of carbon storage potentially suitable for long-duration NET. Three of those relate to geological injection of CO_2 via CCS. Haszeldine & Scott [50] considered the readiness of the different technologies, plotted against volumetric impact. A simple graphical summary is figure 7.

From this type of approach, we examine seven of the nine the NET potentially available (ignoring cost and payment for NET services), at the required scale of delivery. We find that technologically viable NET in the years to 2035 are limited to three. Each of these are briefly examined. A fundamental caveat for all three, as discussed in the CCS analysis, is the slowdown of progress, and limitation on deployment through practical human factors. Such factors include (i) the manufacturing ability to move up in scale from laboratory and field test, through to full commercialization and routine deployment, (ii) gaining permissions from environmental regulators and from land planners to build and operate the equipment, and (iii), most important of all, financial profitability and confidence in the political imperative that a fundamental and durable change in operation of the carbon system will be demanded in each country affected.

(b) CCS for BECCS and DAC

As stated above, to achieve a modelled prediction that the climate will stay within 2°C global warming the IPCC AR5 report required the modelled addition of both CCS, and negative emissions by using BECCS. Both of these, and the subsequent development of DAC,

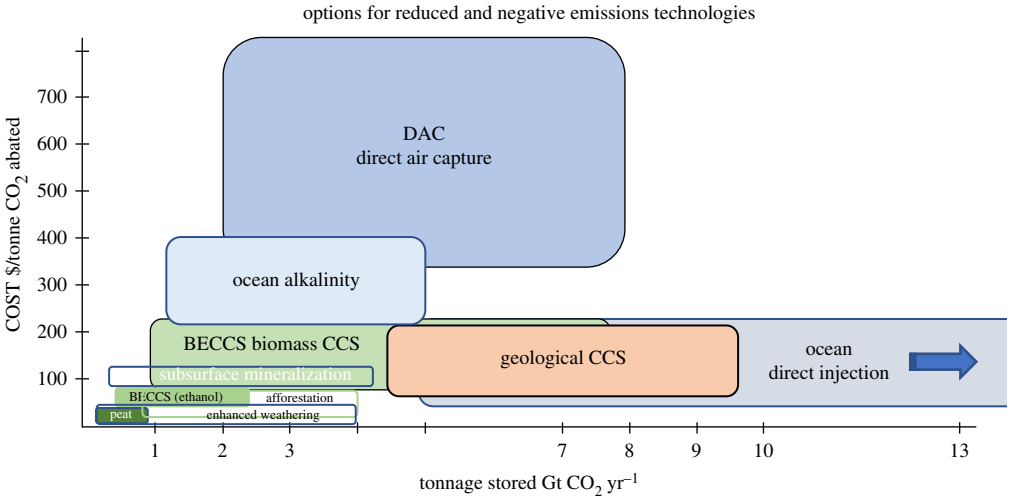

Figure 6. Comparison of semi-quantitative cost and impact of selected NET to remove already emitted CO_2, against CCS options to reduce rates of input. Non-marine NET derived from Scott *et al.* [1]. CCS and marine NET from this article. Estimates to resources for bio, geo and ocean sectors are unrisked, and could be downgraded by as much as 90% through commercial evaluation. Biomass growth and recarbonizing soils including biochar could provide 100 GtC [43,44]; enhanced ocean fertilization and productivity 26–180 GtC [45]; dissolved inorganics in the oceans 500 Gt C [46]; natural minerals and rock weathering or *in situ* injection 90 000 Gt C [47]; waste mineralogies 50 GtC [48]. Geological storage as CCS in depleted hydrocarbon fields and saline formations could be 100–1000 GtC [49].

assessment of CCS and NET technologies

technology	theory	pilot operates	full operation	monitoring	secure	finance
CCS						
BECCS						
soil carbon and biochar						
enhanced weathering						
afforestation						
subsurface mineralization						
ocean direct injection						
ocean alkalinity						
direct air capture						

Figure 7. A schematic progress chart for different stages in the emergence of a CCS or NET to be applied at commercial reliability, cost and scale. Green is ready, yellow is partly achieved and red is untried, undeveloped or failed. A lot of progress remains to achieve.

require immense tonnages of secure CO_2 storage. This will use the same legal, regulatory and technological principles of CCS. If CCS fails to become established, then it will be progressively more difficult for biomass developers to become responsible for planning of capture plants with transport and storage. Apart from the business models, it is not clearly apparent that there will be additional learning needed to develop storage for BECCS or DAC—just site-specific evaluations for applying generic 'conventional' CCS to storage of CO_2 from BECCS and DAC.

BECCS, like biomass itself, can come in many forms. Capture of high-concentration CO_2 from manufacture of corn-based methanol is already underway at Decatur Illinois. Projects to capture high-concentration CO_2 streams from brewing and distilling are easy to envisage, but do not yet seem to have been deployed. Developing BECCS on combustion of wood at large scale has not yet been achieved. Large power plant can readily convert from coal to combustion of biomass, like Drax in the UK, but CCS has not yet been added.

But a second difficulty arises in verifying the provenance and carbon balance sustainability. Provenance authentication of sustainable biomass supply will be as important as verifying the capture efficiency of BECCS or the ensuing CO_2 storage. Fuels such as sugar cane, which harvest annually, can more easily match harvesting tonnages to re-growth within a year or two. By contrast, a convincing assertion that woody biomass provides re-planting to sustainably balance carbon stocks [51] in anything less than 40–100 years still seems hard to achieve without CCS [52]. Third, if CCS is to become deployed onto biomass, then a global mitigation industry of the size envisaged by IPCC will require immense areas of land conversion from crops to biomass.

DAC remains a holy grail of negative emissions technologies, and the first pilot projects are only now emerging. There is no consensus on the methods of CO_2 separation from air. Irrespective of the technology chosen, there is a fundamental disagreement on the amount of energy and work to be undertaken. Brandani [53] takes an approach rooted in established process engineering, and finds that energy consumption during separation will be 10 times that for more concentrated flue gases. A similar approach was followed by House *et al.* [54] who calculated 400 kJ of work per tonne of CO_2, with costs consequently being around $1000 per tonne CO_2. By contrast, Realff & Eisenberger [55] propose an exothermic capture process where the only energy cost is a 10 kJ per mole entropy input, so that capture costs are minimal, but assume that sorbent materials are rejuvenated with 'zero cost' low grade heat. Operational projects, such as ClimeWorks in Switzerland, use 'low cost low carbon' electricity to enable separation of CO_2 from air. This at present is more like a circular economy operation to recreate hydrocarbon fuel, and not a DAC. There is not yet a really clearly operational DAC fully linked to long-duration storage destination.

(c) Subsurface mineralization

Subsurface mineralization is envisaged as injection of CO_2 directly into the subsurface in suitable rock types utilizing reactive mineralogy to precipitate a mineral form of CO_2. The principle is that divalent cations (e.g. Ca^{2+}, Mg^{2+} and Fe^{2+}) can readily and rapidly form carbonates, in reaction with carbonated brine. This process has never yet been tested at commercial scale, although propositions from mining companies such as DeBeers [56] are being evaluated to convert large tonnages of mine wastes with suitable mineralogy into carbon sinks. This can, in principle, use existing borehole technology, and access very large volumes of reactive rock mineralogy without societal delays for planning and enacting supply chains for immense extractive quarrying. Matter *et al.* [57] have trialled the injection of CO_2 dissolved in brine into exceptionally porous recent basalt sediments and lavas in southwest Iceland, as part of the CarbFix experiment. This very small-scale trial mineralized 120 tonnes of aqueous dissolved CO_2 within a few days, at a very low cost of only a few $ per tonne CO_2 abated. This type of injection, could within years be scaled up in number but not greatly in size, and could technologically use very large volumes of uniquely reactive basalt glass and lava in central Iceland to store many hundreds of millions of tonnes of CO_2. Even assuming that a business payment could be made, and that shipping can be rapidly built to transport CO_2 to Iceland, gaining public permission will be a limiting step. The theoretical storage resource available from ocean floor basalt, which is more difficult to exploit

could be 18 000 Gt CO_2 [58]. Similar trials in geologically much older and less reactive and less porous Colombia basalts of Washington, USA, had less success, due to lesser permeability and reactivity of older basalt, and use of liquid CO_2, rather than reactive aqueous dissolved CO_2. However, in both trials, it is difficult to precisely verify the quantity of stored CO_2. Current work is evaluating the potential for specific geological sites where ocean floor rich in reactive olivine and pyroxene minerals occurs, with resources of thousands of millions of tonnes [59]. These experiments are close to natural processes, and clearly work at an adequate timescale and at a low cost and minimal environmental impact due to minimizing extractive quarrying. It is not yet known how to scale up borehole injection to accept tens or hundreds of millions of tonnes CO_2 per year. Methods of monitoring to verify the certainty of CO_2 sequestration into minerals, before climate action payments may be made, are not yet clear. It is these types of barriers, through legal permission and legislation, environmental operation practice, ability to verify and profitability, which have delayed the practical progress of 'conventional' CCS for about 20 years.

(d) Enhanced weathering

Conceptually this approach attempts to identify the natural reactions which consume atmospheric CO_2 through reactions with rock forming minerals. The work of Schuiling & de Boer [60] proposes that deposits of the relevant minerals could be quarried, crushed and dispersed at the Earth's surface or along coastlines where exposure to air and ocean with small particle sizes would produce rapid reactions to sequester CO_2 from the atmosphere. This storage on land is conceptually as carbonate minerals, or in soluble carbon and cationic complexes. If applied to watercourses inland, carbon complexes are ultimately transported through freshwater drainage to the ocean. This could be very low cost, potentially \$5 to 10 per tonne of CO_2 abated. It is likely that there would be extremely large surface environmental impacts, because the tonnage of minerals quarried and transported is required to be similar to the tonnage of fossil carbon extracted annually. The products of reaction remaining on land, or at the site of weathering are the resistate residues, such as silica. Thus the ultimate fate of most weathering products is transport to the ocean. The capacity of ocean to accommodate a vast engineered flux of soluble cations plus bicarbonate, is best considered as ocean alkalinity. It is not clear what the legal or regulatory position is or will be, if enhanced weathering is engineered on land or coasts, with the deliberate intention of discharging the naturally reacted products into the ocean via natural groundwater and surface hydrogeological flow processes.

(e) Ocean alkalinity and direct injection CO_2 dissolution

Climate warming is causing ocean warming, which increases sea level, due to water expansion. About half of the excess CO_2 emitted by human action since 1600 is dissolved in the upper ocean. This is causing an increase in ocean acidity, currently measured about 30% more than pre-industrial. These effects produce detrimental consequences which kill corals [61] and thin-shelled planktonic life. The whole ocean contains about 130 000 Gt CO_2 (38 000 Pg C), 90% of which is bicarbonate ions (DIC, dissolved inorganic carbon). A typical concentration of DIC at mid-depth is 2.3 mmol kg^{-1}, and residence time is 200 000 years. That residence time is long enough to divert and securely store modern CO_2 to enable climate recovery. Deep ocean water contains about 15% more dissolved CO_2 than in present-day shallow water. This is due to ancient recharge of deep water during periods of higher atmospheric CO_2. Logically, there is a possibility to directly inject large tonnages of CO_2 into the deep ocean, where it will dissolve to marginally increase the existing CO_2 content and acidity. Marchetti [22] was perhaps first to propose using downwelling in ocean currents as sites to inject large tonnages of CO_2, which would be carried securely into the deep ocean without affecting surface ecosystems. He calculated for his 'GigaMixer' that CO_2 injection at the Straits of Gibraltar would dissolve into the 10^{14} tonne yr^{-1} marine water deep outflow of the Mediterranean into mid-waters at 1500 m depth. These waters spread and mix across the northern Atlantic Ocean without affecting bottom life or shallow planktonic life. If

0.1 mmol kg^{-1} (6 g per tonne) of DIC is added to surface water as it sinks, then 600 Gt CO_2 yr^{-1} could be added into mid-depth ocean water from that single GigaMixer site. That is much more than the IEA calculation [62] of 32 Gt yr^{-1} CO_2 emitted by all fossil carbon use as energy. This is very capable of meeting the current annual increase from fossil fuel and industry GHG emissions of 2% yr^{-1} to 36.8 ± 2.0 Gt CO_2 eq yr^{-1} in 2017 calculated by the Global Carbon project, within a total global emission of 41.5 ± 4.4 Gt CO_2 eq yr^{-1} [63].

This direct injection remedy could potentially be deployed rapidly, within years and grow to a large scale. The arithmetic of mid-depth CO_2 disposal into ocean water is attractive, but even assuming the technology for shipping the CO_2, and the ability to inject and dissolve liquid CO_2 at these depths exists, the usual obstacles emerge as blockages. How will sufficient CO_2 be collected or captured? How will this CO_2 storage be monitored and verified? Can it be reversed? Who will pay and why will they pay? Not to be underestimated are the legal obstacles to disposal of CO_2 in this manner—which will be all the ocean conventions prohibiting dumping at sea.

Sea dumping opposition was legally tested in 2001 by the CO_2 ocean sequestration field experiment proposing to inject 60 t CO_2 in 800 m deep water offshore Hawaii. The 60 tCO_2 injection plan was blocked by environmental opposition [64], and so transferred to a site offshore of Norway, but was again blocked by public and political opinion.

Ironically, modelling suggests [65] that even if massive CDR is undertaken to reduce warming, then the consequences of ocean acidification are already locked in. Continued acidification is now inevitable, so cannot be used as an objection to engineered ocean CDR. Existing excess anthropogenic emissions of carbon into the atmosphere are now equilibrating with the ocean and will inevitably continue to equilibrate during the next centuries. Even if a 'do nothing' approach is taken because of finance, legal and technological complexity, then emitted CO_2 will end up in ocean water. The oceans have capacity, so the debate is really about the legality and cost of intervention to accelerate that CO_2 dissolution into the oceans.

As mentioned previously, enhanced weathering propositions ultimately rely on increasing ocean alkalinity, by transport of metal cations from weathering zones. To directly inject CO_2 to form DIC in the ocean is a more direct method, with no quarrying, mineral transport, or resistate mineral and trace element side products. By contrast, most propositions for increasing ocean alkalinity have revolved around dissolving minerals into ocean water either from land run-off of enhanced weathering, on beaches, by enhanced electrochemical weathering, or dissolution by liming the ocean, or by dissolution of finely ground limestone sometimes in direct contact with untreated power station flue gas [46]. The pathways and fate of reactants are complex, with combined chemical, biochemical, temperature, pCO_2, pH and physical pressure acting though intersecting cycles of time and space. Most understanding of enhanced CO_2 aq dissolution is based on a conceptualization of adding $CaOH_2$ as the simplest alkalinity. Residence time of carbon is then calculated to be 100 kyr—both quick enough and long enough to act as a durable measure to mitigate against 1.5°C or 2°C warming. It is, however, essential to understand the impact of alkalinity change on the oceanic carbon cycle, especially in shallow surface waters. Estimated costs [46] for these ocean alkalinity technologies are $10 to $190 per tonne CO_2 stored (not abated), and overlap with 'conventional' CCS estimated storage costs of 30–100 $/tonne CO_2. For shallow ocean alkalinity storage, then the costs and logistical difficulties of acquiring, extracting and transporting the mineral reactants are very significant—between 1 and 3.5 tonnes of raw material for each tonne CO_2 captured.

To consider the timescale for material impact to occur on the emissions problem, Renforth & Henderson [46] estimate for cement emissions, the timescale until material capture is achieved. They base this on historical growth rates for new infrastructure technology, such as tractor mechanization (5% in the USA) or road-building in the post-war UK (15%). An illustration of the rate of growth outcome is that 12% annual growth is needed for the NET ocean liming; that could match 4.2 Gt CO_2 yr^{-1} of the present global cement production emissions but not for 45–60 years into the future.

Overcoming the regulatory and legal safeguards of the global ocean commons will take significant time, in the order of (many) tens of years. The United Nations Convention on law

of the sea (1982) enshrines basic principles for new and emerging marine activities. The 1972 London Convention, and its associated 1996 London Protocol, are considered to be capable of protecting against marine geoengineering. A resolution change proposed in 2008 was adopted in 2013 to specifically include regulation of ocean fertilization activities [66]. Thus, it is apparent that timescales of international treaty changes and permissions are measured in decades. Consequently, even though increasing the bicarbonate content of ocean water could dispose of 500 GtC, this would require an amendment to the London Protocol to allow mineral matter addition for the purpose of affecting the climate. Thus cultural, regulation and engineering inertia mean that this is unlikely to be material before a 1.5°C warming has been passed around 2030, but may be of use to limit a 2°C warming.

8. Summary and proposals for action

(1) Excess CO_2 emissions, derived from fossil carbon and modern biocarbon use, will play a critical role in climate forcing during the next 100–1000 years, and the resultant warming will continue for tens of thousands years. To reach a sustainable level of net-zero emissions by the mid twenty-first century, CO_2 emissions must be reduced by a compounded rate of an extra 1100 Mt CO_2 yr^{-1}, each year. Methods of reduction needed are zero carbon energy technology deployment, fuel-switching, improved efficiency and behaviour change and, examined here, CCS, CO_2 Capture and Negative Emissions Technologies.

(2) Across whole economies CO_2 CCS in geological reservoirs, leading to BECCS and DAC for negative emissions, is a direct, technologically understood and practically proven mitigation action. Analysis of all CCS projects shows that only CO_2-enhanced oil recovery is currently viable commercially. From zero in 1996, the rate of CO_2 capture intended for climate mitigation storage has increased to a current rate of 60 Mt CO_2 yr^{-1}, which is approximately 100 times lower than required by 2050. Current CCS development projects in the USA are expected to cease in the early 2020s when grant funds expire. Even if funds remain available, our extrapolation of past progress, predicts only 700 Mt yr^{-1} CO_2 storage globally by 2050, which is 10 times lower than required.

(3) Abandonment of CCS now would also exclude the development of expertise and preparation of future CO_2 storage options for BECCS and DAC. This would eliminate the majority of scenarios in IPCC AR5 (2014) which stay beneath 2°C warming, and make an RCP 4.5° warming 60% probable by 2100. Paris 2015 commitments can only be met if CCS is part of the solutions.

(4) Relaunching CCS requires a focus not on coal or high cost clean electricity, as in the years since 1994, but a positive focus on value. One such value is atmosphere protection and air quality health benefits. Developing CCS in a region with a good knowledge of the local subsurface has a 10 year lead-in time to choose an appropriate storage site, and a further 5–10 years to evaluate the specific site, and develop storage regulations and acquire permits. Government interventions are needed immediately to start evaluation of geological storage options held by individual countries. Enactment of full-chain CCS will also require Government to aid creation of transport networks, which can be sold once commercial [36]. Crucially, national Governments have to reduce the price difference between processes with CCS and processes without CCS. One solution is to tax carbon emissions. A more simple and direct approach may be for governments to create Certificates of Storage which can create a competitive market for verifiable carbon storage. That would develop to discover the best national solutions, at least cost of storage [36].

(5) There are about 10 NETs which could produce impact of more than 1000 Mt CO_2 yr^{-1} reduction in emissions, if fully deployed. Most of these are still conceptual, or in the early pilot stage. To retain warming to within 1.5°C, large-scale deployment is needed within 10–20 years. Three of these NET could potentially be made ready for rapid deployment

in that timescale (see points 6, 7, 8). In addition, CCS is ready to operate on specific types of high-concentration CO_2 streams from industrial separations (e.g. fermentation, ammonia), including hydrogen production from natural gas. It is not necessary to wait for all processes to be equally capture-ready. Commercialization requires either a funding or a mandate policy, which could enable hundreds of Mt CO_2 yr^{-1} to be captured and stored before 2030. BECCS can be operated at pilot scale in the short term, but capture of biomass combustion-derived CO_2 at large scale requires more development during the next 10 years. DAC is operating only as test pilots, and will need scale up and cost reduction over the next 10–20 years.

(6) Enhanced weathering can be low cost ($5–20) per tonne CO_2 abated, but requires immense logistics of quarrying and transport of mineral materials to achieve the impact. Mine wastes with reactive mineral cations may be easy places to start. For this NET, DIC ions will run-off the land surface to accumulate in the ocean, affecting alkalinity. This NET may not become legal to implement.

(7) Subsurface mineralization, forming carbonate minerals by direct injection of dissolved CO_2 to contact reactive minerals in the subsurface, has been successfully trialled at a very small pilot [59]. Scale up during a 10 year period, using conventional technology could increase this to significant impact, although long-term evolution of porosity and permeability, thus sustainability of this storage method, has yet to be proven. Regulatory, social and political permissions have not yet been addressed.

(8) Direct injection of CO_2 to mix with, acidify, and disperse into discrete bodies of mid-depth ocean water is conceptually simple to enact. This could dispose of very large annual CO_2 tonnages. However, much greater assurance on dispersion by ocean currents is needed, and this is very likely to be legally contradicted by the London Convention. Increasing ocean alkalinity by liming or mineral treatment of upper waters, could also dispose of large CO_2 quantities, but ocean chemistry and current ecological interactions are complex and poorly known.

(9) Decisions made during the next 10 years on how to store carbon for geological timespans, will strongly control the magnitude of risk of global change into the next 100 years. These global change hazards include ocean acidification, sea-level rise, global warming and the consequent ecosystem disruption and human migration. Faced with the current option of lower cost investment to mitigate uncertain, but very likely, and extremely high-impact future changes, it seems scientifically negligent, politically myopic and sociologically disastrous to avoid action. Practical action is now overdue, as CO_2 storage deployment will, even now, be unable to meet 2050 requirements from climate change mitigation modelling. For all states worldwide, an evaluation of CO_2 storage is needed, to create options to act on from the mid-2020's in support of commitments to Paris 2015, and for the sustainability of national human populations.

(10) The two key local actions for individual national Governments are (i) to identify, assess and quantify their own potential for geological CO_2 storage and (ii) to create a simple, rapid, controllable, verifiable and long-term incentive to undertake storage of CO_2. This is most simply achieved by allocating Certificates of Storage onto producers of fossil carbon, combined with a defined mandate to permanently store an increasing percentage of produced carbon every year, calculated backward from the requirement to reach net-zero by 2050.

Data accessibility. Electronic Supplementary Material contains a full database of CCS projects globally on which the modelling in Fig 4 and Fig 5 was based.

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